BOA: Asbestos Abatement Robot System and Field-Trial Experiences

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I. ABSTRACT

The *BOA* (Big-On-Asbestos) system is a mobile pipe-external robotic crawler used to remotely strip and bag asbestos-containing lagging and insulation materials (ACLIM) from various diameter pipes in (primarily) industrial installations. Steam and process lines within the DoE (Department of Energy) weapons complex warrant the use of a remote device due to the high labor costs and high level of radioactive contamination, making manual removal extremely costly and highly inefficient. Currently targeted facilities for demonstration and remediation are Fernald in Ohio and Oak Ridge in Tennessee.

II. INTRODUCTION

Asbestos insulation abatement has been, and still is, a big problem in renovation and dismantlement [3], since EPA (Environmental Protection Agency) and OSHA (Occupational Safety & Health Administration) regulations are strict on removal procedures and worker safety [4], due to the carcinogenic nature of the insulation product (despite ongoing disputes) [5].

The DoE owns many chemical processing plants across the U.S., which are scheduled for dismantlement. Most of their steam and process lines have been insulated with ACLIM and hence warrant special attention, especially due to the high potential of contamination with contaminated fluids and particles. Hence, these lines within the DOE weapons complex warrant the use of a mechanical and remote device due to the high costs of abatement, making manual removal and disposal extremely costly and highly inefficient.

The DoE has funded a two-phase program at CMU to develop an automated system to strip insulation from their process pipes. The two-phase program has progressed past Phase I with a proof-of-concept prototype development and testing scope, and is currently in Phase II. As part of the current scope, a complete regulatory, market and cost/benefit study has been completed. Current efforts are targeted towards the design and implementation of a prototype system to abate steam and process lines in the 4 to 8-inch diameter range at a DoE facility by March/April 1997. In the first-phase effort completed in December 1994, we developed and tested a proof-of-concept prototype system using preliminary locomotion and removal systems, with fiberglass insulation as a surrogate material (see Figure 1) [9].

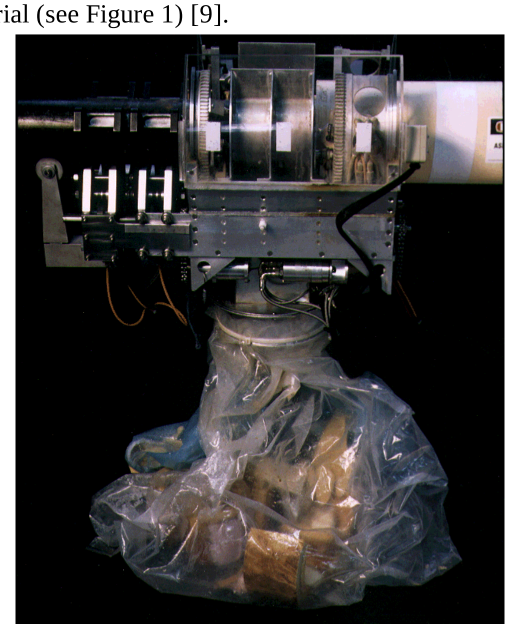

Figure 1*: BOA* Proof of Concept Prototype Robot

III. PROBLEM STATEMENT

The main challenges in developing an automated asbestos abatement system lie in the areas of process, operations and regulations ([1],[2],[11]). One has to deal with insulation and lagging materials of almost all possible forms and consistencies, which make any material handling mechanism hard to design. Furthermore, the device must be able to work in existing facilities which were not designed for human abatement activities in terms of reach, access, etc., and even less for the use of a machine to perform the abatement job. And lastly, the entire operation has to meet the stringent regulations drafted and enforced by OSHA and EPA, which are mostly concerned with keeping fiber counts below acceptable levels, while enforcing that only allowable work practices be employed during the abatement process. And of course the last hurdle before a system could truly be termed successful, is that it has to be able to save the abatement contractor money, while doing the job faster, safer and better than a human asbestos worker could.

Representative ACLIM materials we are concerned with, include the lagging materials, such as aluminum, straps, screws and wires, and the insulation material, typically friable[1], or as hard as CalSil. A pictorial view of these materials is shown in Figure 2.

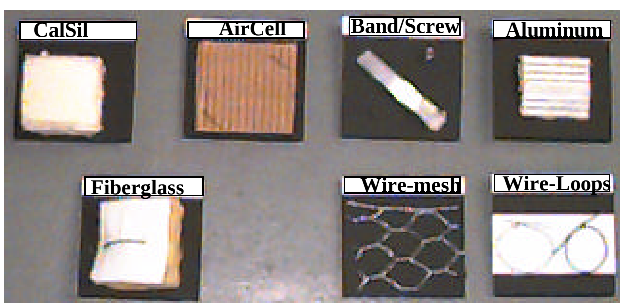

Figure 2: Samples of lagging & insulation material

IV. PRELIMINARY RESULTS

It was determined [9] that such a self-propelled, negative-pressure mini-containment system could meet EPA and OSHA mandated fiber-count levels during abatement operations, and that automated removal operations on piping could achieve a high removal rate. Using a mechanical cutting method (circular diamond-grit coated blade), we were able to achieve a net abatement rate of 4 ft./hr., which we knew we had to improve on to make the system more cost-effective. Compressing the material off the pipe once cut, was not sufficient to guarantee removal 100% of the time without some form of human assistance. This result lead us to the realization that a truly reliable and omni-directional cutting system was needed. The use of fiberglass as a surrogate was changed to Calcium Silicate (Calsil), since it was termed more akin to asbestos-containing material (ACM) in the field. This change made in-situ compression of the ACLIM unrealistic and the need for water-assisted/misted cutting and size reduction necessary, further aiding to reduce loose fiber emanation.

Based on these main and other secondary results, the DoE review panel decided to continue the project into Phase II. A revised statement of work for Phase II called for improvements and refinement to the design of the robotic removal head and locomotor system, further guided by a regulatory analysis and a market study and cost/benefit analysis to determine regulatory and performance requirements, market size and commercial potential of such systems for the DoE and within the abatement contractor industry.

V. COST BENEFIT ANALYSIS

The overall study [5] clearly highlighted guidelines in the areas of regulatory compliance and certification, potential market sizes in the DoE and industry, as well as overall performance requirements and system-cost boundaries in order to be competitive and achieve substantial savings in the thermal insulation abatement market segment.

A. Regulatory Analysis

As part of the regulatory analysis, we charted a 'certification' path for any alternative abatement method proposed to EPA and OSHA. Even though OSHA/EPA do not certify equipment for use in abatement jobs, they do specify system performance in terms of allowable exposure limits (which aids somewhat in system design), work practices (process of using abatement techniques and equipment) and approval processes (permitting, notification, etc.). From a design stand-point, we will have to ensure we meet the fiber-emissions level regulations, which currently lie at 0.1 fibers/cc - as spelled out in 40 CFR Part 61 [8]. These restrictions imply the use of static and dynamic seals, positive airflow at all times, proper wetting and fiber-sealing and a proper deployment procedure to avoid any fiber release. The 'certification' process that BOA will have to go through, involves the drafting of a technical performance report by an on-site industrial hygienist or project designer with P.E. license which is then submitted to the DC-office of OSHA for review and acceptance - a process spelled out in 29 CFR 1926.1101 (g) (6) [7]. Local, state and regional EPA and

1. defined as turning to powder upon being touched

OSHA officials are kept abreast of the development and are invited to view the deployment and check for compliance on top of the required independent air monitoring. A full timeline and a list of deliverables and names within EPA and OSHA have been drafted for implementation during Phase II.

B. Market Study

A thorough review of thermal insulation systems and the asbestos abatement industry within the DoE and industry was conducted [10]. It was determined that the DoE has about 2 million linear feet of <u>total</u> piping (1.5M indoors, 0.5M outdoors) of medium bore-size (4 to 8 in. DIA.) in need of abatement, collected in the six major sites (Savannah River, Hanford, INEL, Oak Ridge, Rocky Flats, Fernald). A breakdown by site and indoors/outdoors is given in Table 1 below.

DoE SITE	Outdoor	Indoor	TOTAL
Savannah Riv.	110,000	562,000	672,000
Hanford	100,000	300,000	400,000
INEL	60,000	189,000	249,000
Oak Ridge	30,000	184,600	214,600
Rocky Flats	60,000	186,000	246,000
Fernald	70,000	48,700	118,700
TOTAL	430,000	1,460,300	1,890,300

Table 1 :Medium Bore DoE piping breakdown

The industrial market size was determined to be about 33.5 million linear feet each year over the next 10 years [6]. We believe that a BOA-like system, attacking only a portion of that market (4 to 8 inch diameter piping) currently abated with glovebags (22%) and then only in more sizeable installations where clearances are available for the robot to work on pipes, would be applicable to up to 0.5 million linear feet <u>total</u> within the DoE and about 1.5 million linear feet <u>a year</u> within the industrial market segment in the United States.

C. Cost/Benefit Analysis

Based on the potential performance of a robot abating at a rate of 30 linear feet per hour, compared with about 3 to 6 feet in DoE/Industry, with associated per-foot abatement costs ranging between \$25 and \$150 for Industry/DoE, it was determined that substantial savings could be realized with the use of such a robot system [10]. Overall abatement costs could decrease between 25% and 50%, depending on whether the system replaces a current glovebag or full-containment method. Overall savings were thus computed to lie between \$10 million and \$15 million for DoE, which does not even count savings due to reduced radiation exposure, work-crew reduction and insurance savings, overall worker safety and potential litigation cost savings. Potential unit sales to DoE (and/or its M&Os and subcontractors) and commercial asbestos abatement contractors were estimated to be between 150 and 300 units over the next 7 years, depending on the size of the contractor and job, as well as the final production cost of the system.

VI. SYSTEM TESTING

The design of BOA went through two iterations, allowing us to test and analyze the performance of the clamping and cutting system, the two crucial elements of the system. We determined that three-point contact was essential for stability, allowing two clampers to always support the robot at all times. The cutting system had to be omnidirectional and combine metal-cutting and water-blasting abilities in a single design, thereby reducing the number of steps and cycle-time of the process, thereby increasing throughput. A more detailed overview of the design stages and simulation and testing program for BOA, are contained in [9].

VII. SYSTEM OVERVIEW

The overall system configuration of the *BOA* asbestos abatement system is shown in Figure 3. The abatement head is located on a pipe, and tethered to the off-board logistics support and control units. Connections between the head and the logistics unit include power, control and feedback lines, water and encapsulant lines, as well as a 4-inch diameter vacuum hose. A jib-crane is used to emplace and remove *BOA* on and from the pipe upon start-up and around obstacles. The off-board logistics are comprised of a diesel-powered electric generator, a 1,000 cfm industrial HEPA-vacuum system, a cyclonic waste-bagging system, and a water-separator system for removing water from the waste-stream. A pressurized water pump and encapsulant system are used to cut the insulation and wet the removed sections to trap any loose fibers. A central controller box controls, coordinates and monitors all system parameters and interfaces to a human operator via s simple touch-pendant.

The crawler itself (also termed the abatement head), dubbed *BOA*, consists of a locomotor and remover section, where the locomotor is responsible for clamping and inching along the pipe, while the remover contains all the systems needed to remove the ACLIM from the pipe to the required cleanliness levels. A picture of the overall abatement head and the individual locomotor and remover are shown in Figure 4 in a CAD and photographic rendering.

The abatement head is able to automatically crawl along the pipe and remove insulation via its remover section. The locomotor is based on a set of clamping units that are interconnected via the locomotor stages to allow the system to crawl in an inch-worm fashion. A perspective view of the locomotor section (with the attached clamper units), is shown in Figure 5.

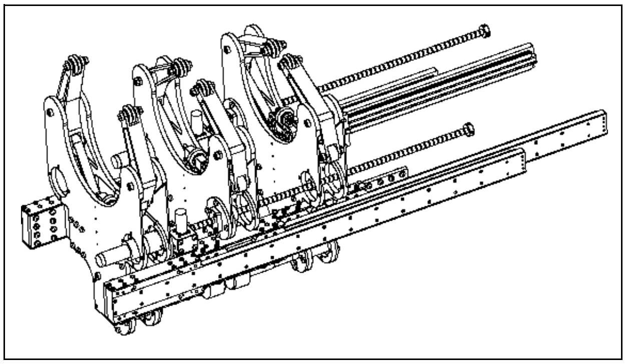

Figure 5: Overview of locomotor system

The clamper is a simple four-bar linkage system operating on three-footed contact rollers to allow centered and misalignment during the clamping operation. By using three clamping units, we will guarantee stable walking and removal operations, since two clamps will always be attached to the pipe. Figure 6 shows the overall clamper configuration, while Figure 7 shows the open and closed configurations of a ‘dissected’ clamper.

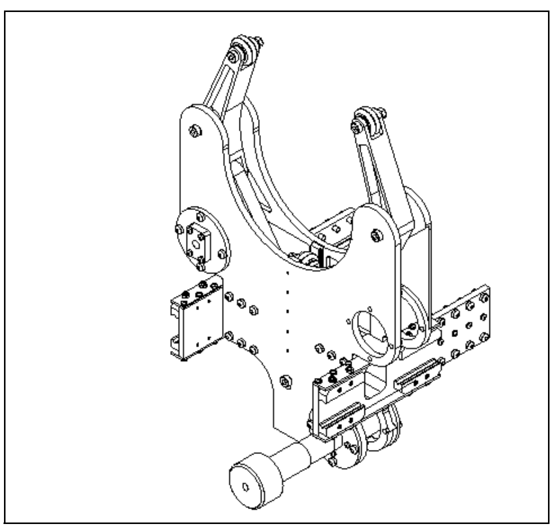

Figure 6: Overview of clamper system

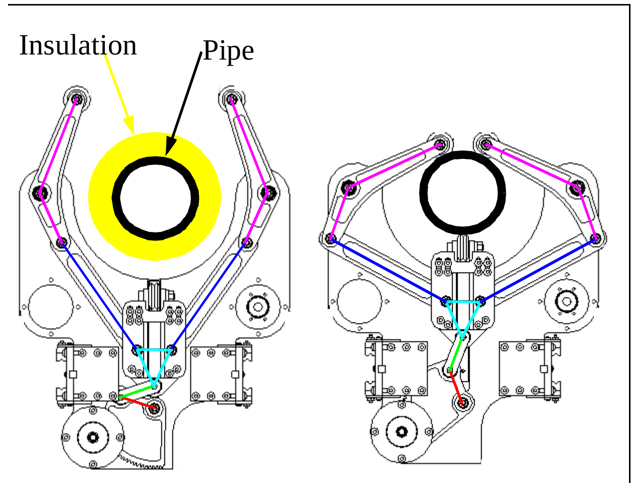

Figure 7: Clamper Overview and extreme positions

Note that we are using a simple three-point contact scheme, actuated through a gear-driven hybrid four-bar linkage mechanism. Orthogonally-placed v-groove rollers on the ends of the three contact points ensure that each clamper has a self-centering effect without losing the ability to stay clamped onto the pipe.The remover is based on a rotationally mounted set of three omni-directional hybrid endmill/water-jet cutters that are used to dice the insulation into 2-inch chunks as the abatement head walks along the pipe. An inside view of the rotating cutter-head plate is shown in Figure 8. The cutter-head is a customized hybrid endmill/water-jet system which allows the head to cut through all forms of metallic lagging and strapping, while being able to cut through insulation without damaging the pipe and without being susceptible to a variety of alignment and obstacle issues.

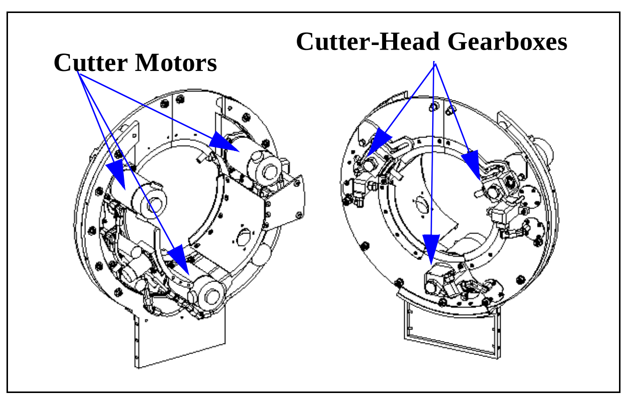

Figure 8: Inside view of the rotating cutter-plate heads

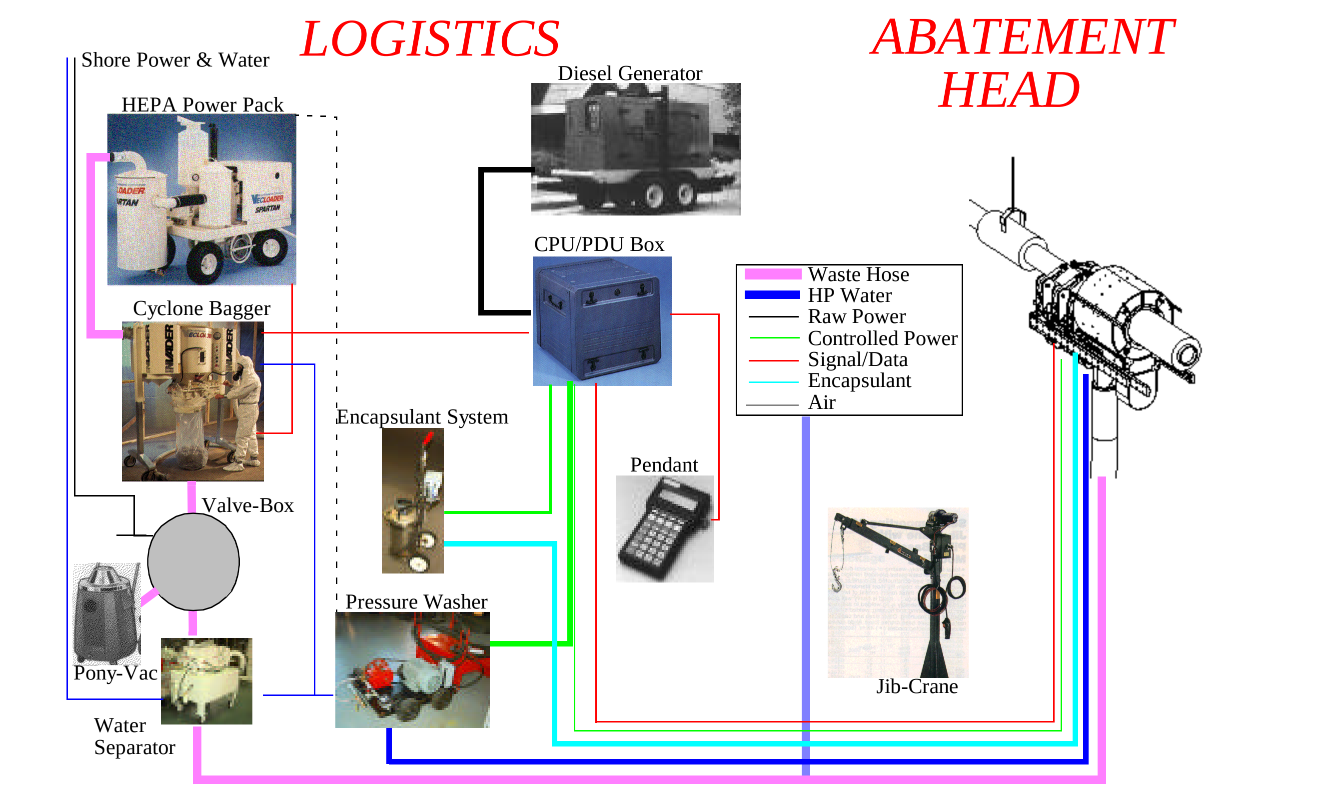

Figure 3: Overall system architecture of the *BOA* asbestos abatement system

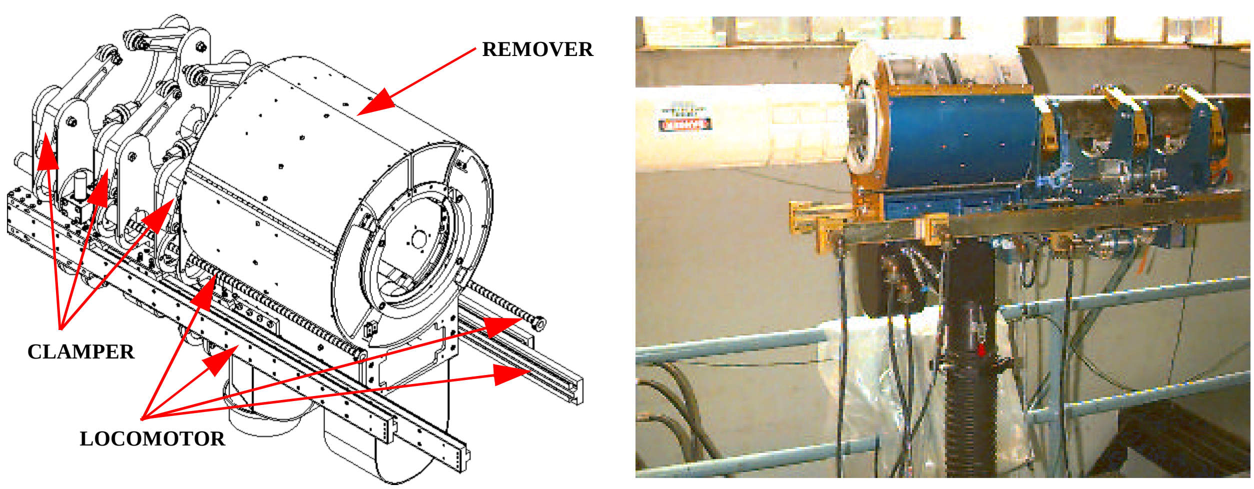

Figure 4: Abatement head views in CAD and prototype picture (shown on pipe with insulation abatement underway).

A perspective and view of the cutter-head is shown below in Figure 9.

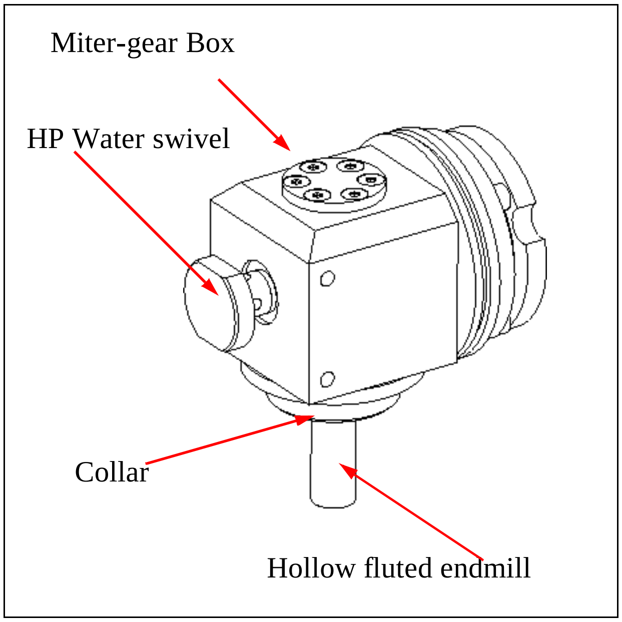

Figure 9: Hybrid cutter-head system

The cutter system performs a combination of circumferential cuts via the cutter-plate heads by rocking back and forth through a $^{+}/\text{-}\ 60^{o}$ angle, shown in Figure 10 (notice the coloring scheme on the cutter endmills), and then combines with a set of forward and backward

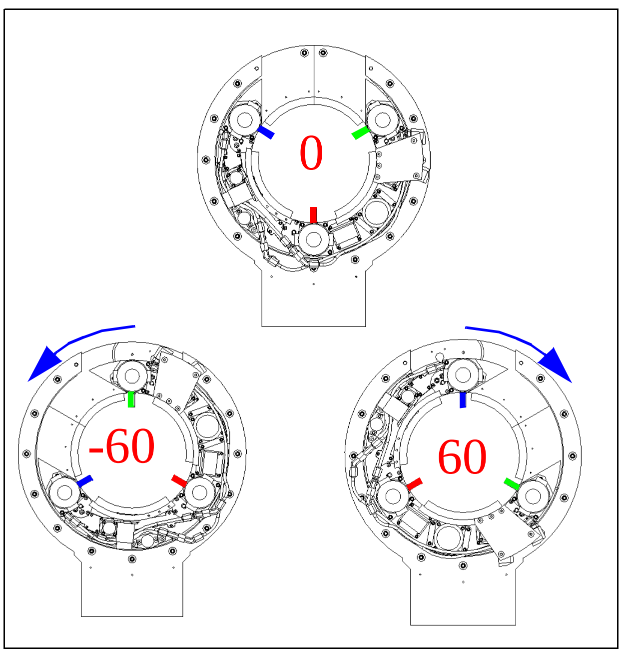

Figure 10: Circumferential cutting sequence

locomotion strokes to 'dice' out chunks of maximum size that can freely tumble out of the removal chamber and travel through the waste-hose uninhibited. Experiments to date have shown that cubes 2.5 inches on side, including aluminum lagging pieces of the same size, and even 24"-long bands (strap cut in only one spot) can all be conveyed through the waste-hose using the 1,000 cfm vacuum system. This type of cutting was determined experimentally to be the best, after trying many other methods (slicing, compaction, etc.).

The cutting and nozzle-blasting actions are combined to dislodge the chunks from the pipe and clean the pipe (Figure 11). The removed insulation and cutter waste-water are vacuumed away from the system through the vacuum hose, which is attached to the bottom of the abatement head and leads the material away from the pipe and to the off-board water separation unit (which recycles the water for cutting), and subsequently the cyclone bagger system.

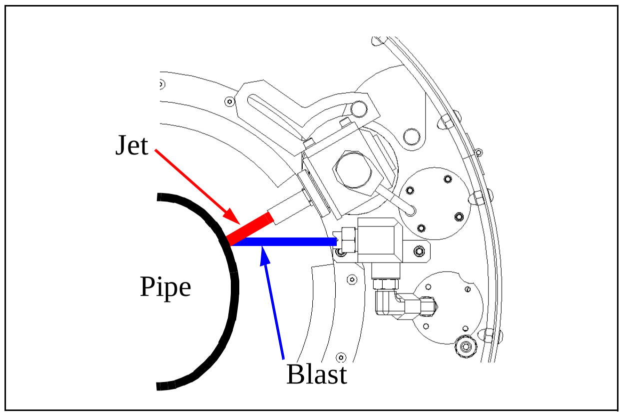

Figure 11: Remover cutting and blasting jet systems

The system is able to size-reduce the ACLIM into small chunks as sown in Figure 12.

Figure 12: Original and size-reduced ACLIM

BOA is currently sized to work on 4-inch diameter piping, but could easily be scaled to larger pipe-sizes[2]. Its productivity is predicted to be between 30 to 40 feet per hour. The abatement head is designed to get around hangers by itself, by stepping around/over them, but without removing the insulation immediately around the hanger. Furthermore, human interaction is needed at major obstacle locations such as valves, junctions and bends. A human is in general only needed to place BOA on the pipe and handle it around obstacles. Left-over small sections of insulation around hangers and obstacles can be readily and quickly abated using glovebags and a single asbestos worker that follows the robot along its path.

Fiber-containment is achieved by sealing the entire system around the pipe, creating a high-velocity entrapment system around all seals (using the vacuum system as a waste-transport means and a vacuum means) and inside the removal module, wetting the insulation and sealing the exposed pipe, while monitoring air-quality around the system and thus obviating the need for a complete containment-area setup. This fact alone represent a major potential cost savings in overall abatement jobs due to the relative expense incurred in preparing the site for the asbestos abatement.

VIII. DEPLOYMENT ISSUES

Based on the study period at the beginning of Phase II, we also developed a new operational scenario reflecting the guidelines and lessons learned from the study itself. A good way to explain the scenario is to depict the two types of possible deployment scenarios, namely indoor and outdoor, as shown in Figure 13.

The entire system is shipped to the site on a flat-bed towed-trailer, where all the logistics units are set up. Assuming no available on-site power, a diesel-generator is used to provide the power for all systems. The HEPA vacuum is set up 300 feet away from the abatement site, to minimize noise levels, and hoses and cables are run to connect the vacuum, electrical and water systems to each other. The water-separator is filled with water, as it serves as the reservoir for the pressurized water pump used for cutting and blasting the pipe. Once the control box is hooked up, the human operator performs a checkout procedure of the entire system, including the robot located in its storage/transport container. Upon successful completion of the start-up, the jib-crane used as the positioner, is emplaced onto BOA, and the complete abatement head is lifted off the transport pipe and brought to the section pipe that has previously been cleared to begin abatement. Once the head is firmly attached to the pipe and the positioner is removed, all systems are automatically turned on and the fully automatic abatement cycle begins.

During normal operations, one would have one operator with the pendant close to the on-pipe crawler monitoring it and overseeing its operations, while a second operator would be needed at the bagging station, as the waste material arriving from the abatement head needs to be batch-removed out of the cyclone separator every 10 minutes. A backup HEPA system is ready to be energized in case of major HEPA-Vac failure as well as during the bag-out cycle. The entire system has also been designed to

2. smaller-bore piping is bagged and cut out of the network and disposed of with the insulation still on the pipe - a stationary floor-mounted *BOA*-like system could tackle this market as well!

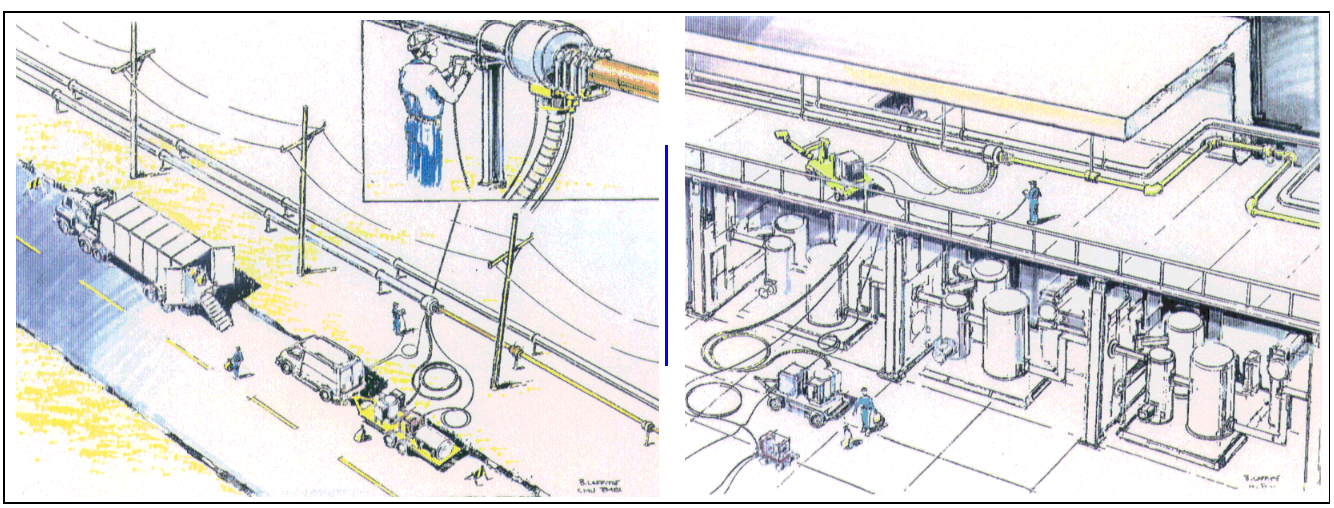

Figure 13: Outdoor and Indoor deployment scenarios for the *BOA* system.

be transportable to work on different floors in industrial buildings so that even extremely-high piping networks can be abated. In general, depending on whether pipes are up high or down low, the use of a JLG (telescoping shooting-boom platform lift-truck) might be required, and our positioner and control pendant have been designed to work on different platforms and at remote locations from the control box.

IX. COMPETING TECHNOLOGIES

The BOA system is unique in that it represents a new class of abatement technology that is currently not available, namely a self-locomoting negative pressure mini-enclosure for automated pipe-insulation abatement.insulation abatement contractors consist of a re-usable glovebag and a remoted vacuum filtering and bagging system as shown in Figure 14.

Figure 14: 'Competing' Technologies

X. OPERATIONS TESTING

The BOA system underwent extensive operations-testing at a full-scale outdoor piping network in August 1997 at Oak Ridge's K-25 site in Oak Ridge Tennessee - the K-25 site was the world's largest gaseous diffusion plant built more than 50 years ago to assist in the production of weapons-grade nuclear fission material. The test-site where the system was deployed is shown in Figure 15.

Figure 15: K-25 Outdoor Test Site

The testing was performed on a 100-foot long section of 4-inch pipe, clad with CalSil, wires, screws, paper and plaster, as well as aluminum-lagging. The system was attached to the pipe and run on the pipe, as shown in Figure 16.

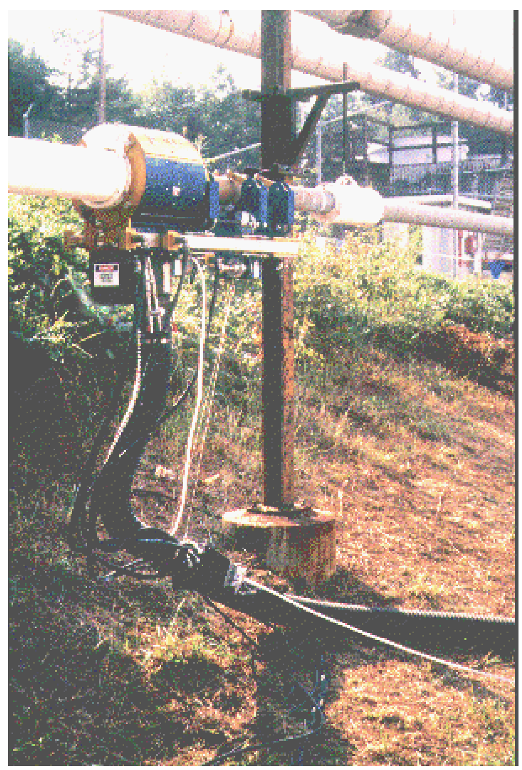

Figure 16: BOA removing ACLIM at K-25

The operator interface was used by on-site DoE personnel, while off-pipe operators continuously bagged the removed ACLIM in a continual operation - both operations are shown in Figure 17.

Figure 17: Operator interface & manual bagging

The system operated at a net rate of 29 linear feet per hour, without the emission of any measurable fibers (independently measured and verified), without the setup of any containment, nor the use of any protective respiratory systems for the operators. The system was also able to pass hangers unaided, spending 5 minutes per hanger, leaving the left-behind insulation to be removed by the two bagging-operators, using standard glovebagging techniques.

XI. FIELD TRIALS

The K-25 site that was slated for the asbestos field trials changed hands to a different contractor, and they were unable to support the field-trials seeing as asbestos abatement was not on their critical D&D activities-list. CMU and FETC actively pursued an alternate demonstration venue, but were unable to locate one readily (commercial sites required unavailable insurance coverage and DoE-sites were not ready or engaged in any sizeable abatement activities). At that point, the International Union of Operating Engineers (IUOE), through a subcontract with the National Institute of Building Sciences (NIBS) was able to locate a large abatement activity in the Pentagon in Washington, DC where BOA could be tested. The goal for NIBS and the IUOE was to develop a clear set of training manuals, safety data sheets, perform air-monitoring, measure abatement rates, develop costing guidelines, etc.

The selected site was located in the ground-floor of the outside ring in the southwest corner (Wedge 1) of the Pentagon - the project was under the control of Radian International and involved the abatement of all asbestos (floors, ceilings, piping, etc.) in the entire pentagon over a 10-year period of the Pentagon Renovation program.

Figure 18: Pentagon Wedge 1 Test Area

The field-trial site was a tall-ceiling indoor area, with 2 sets of 200 feet long pipe-runs hung from the ceiling with hangers at a height of about 15 feet. The insulation was tested and shown to be aircell (15% ACM Chrysotile), with a cheese-cloth and paint-cover (actual abatement would reveal that the sampling locations' lagging was different from the entire rest of the run, which was covered with heavy-duty canvas-cloth which greatly hampered the deployment of BOA). The test-run (prior to it being enclosed for air-monitoring purposes) and ancillary images taken as part of the scouting and setup, are shown in Figure 18.

In order to perform a controlled air-monitoring field-trial, the entire abatement area was to be enclosed in a negatively-pressurized enclosure, with air samples taken in different areas (filters) as well as near any of the abatement equipment as well as the workers operating the system. The Radian crew that was supplied to the project took care of setting up the abatement area in terms of clean-up, emplacing plastic sheeting and installing and running the negative-pressure air-exchange machines. Stationary air monitoring pumps were set up by an outside contractor that then also ran the tests, including the personal monitoring of the abatement crew.

The (mostly hispanic-speaking) crew was trained over a period of 3 days in the use and handling of the abatement head and off-board equipment. A short run of pipe with simulant of cheesecloth over cardboard paper, replicating the insulation make-up that was determined to be in place after a sample was taken in May 1999, was used to demonstrate and train the operators. As part of that training multi-shift crews (a total of 8 people) were familiarized in the use of the equipment (see Figure 19).


Figure 19: BOA Training Session

The off-board equipment was also set up inside the enclosure (Figure 20), except for the computer-enclosure, which was taken and placed outside of the enclosure for monitoring purposes.

Figure 20: Off-board equipment setup

Once the training was completed, and all the associated public-relations affairs were completed (CNN coverage, demonstrations for Pentagon officials, etc.), the system was installed on the asbestos-clad pipe-run and readied for abatement. Background air-samples were taken the night before to reflect the background fiber-count (if any). The installed view of the BOA system is shown in Figure 21:

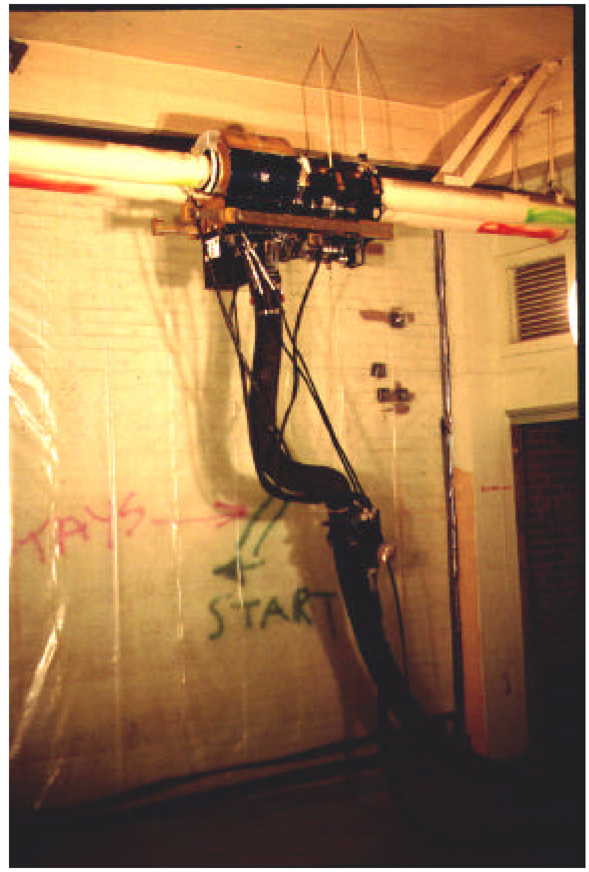

Figure 21: BOA installed on pipe in Pentagon

Once BOA was placed on the pipe, we were not aware of the hand-sown heavy canvas covering on the lagging, which the BOA system was not able to fully cut, as its cutters had not been designed for this task. The BOA system thus only was able to progress very slowly and continually got hung up and required continued human attendance. During the hang-ups, water entered the on-board amplifiers and shorted them out, as well as the encapsulant leaking into the unprotected motor and slide-assembly, thereby ‘gluing’ them together. The net result was that BOA became inoperable and unrepairable on-site due to the number of required spares and the need to replace internal components for which the operators had no expertise/training. The system was thus removed from the pipe, cleaned as best possible and the abatement head enclosed in a bag and then placed inside the shipping trailer on site which was then later removed by the IUOE and stored at one of their locals in Maryland. Even though not scientifically valid, the entire operation of untangling the cutters and removing the abatement head from the pipe, never generated any fiber-levels that violated the OSHA clearance-levels of 0.01 fibers/ccm. The reason for this low level can be seen in the effective wetting and vacuum system inherent with the BOA system

XII. FUTURE WORK.

A meeting was held at FETC between the DoE, IUOE, NIBS and CMU representatives, and it was decided that the system might be returned to a contractor in Pittsburgh that could fully disassemble and clean the system, so that it could be re-delivered to CMU for potential future action, without any asbestos contamination present. In addition, FETC requested CMU to submit a proposal for short-term activities to allow BOA to be repaired and reused locally with wrap-and-cut insulated pipe-section in containment to obtain the NIBS-requested air-samples. Such a proposal was submitted to FETC and we are awaiting resolution on its selection/award/funding status.

XIII. ACKNOWLEDGMENTS

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[10] Schempf et al., "*BOA: Market Study, Cost Benefit Analysis & Regulatory Review - Topical Report*", Draft Version, METC/CMU, Pittsburgh/Morgantown, PA/WV, July 1995

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